Investigation of temperature gradient between ambient air and soil to power up wireless sensor network device using a thermoelectric generator

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ABSTRACT

This paper proposes a study of an energy harvesting system for powering wireless sensor network (WSN) devices. The thermal energy harvesting system used is based on the thermal energy source between ambient air at the soil surface with five depth levels. Measurement was taken for 46 days in a garden area located in Melaka, Malaysia. A feasibility study of soil temperature measurement to obtain a temperature gradient can be used for harvesting by using thermoelectric generators (TEG) modules. Then, the efficiency of TEG with several different configurations based on temperature gradient data has been tested in the laboratory. The results revealed that the depth of soil 6 cm between sensors 1 and 3 will gave the best representation of level average temperature different around 1 ℃. Based on the temperature gradient data, the combination of three TEG SP1848 in a series connection with DC-DC step-up circuit DC1664 will produce an optimum voltage output of about 3 V. This output voltage is enough to operate low power IoT device derived from thermal energy.

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1. INTRODUCTION

Wireless sensors network (WSN) have been a popular topic over the years. Since the Industrial Revolution 4.0 (IR 4.0) era, WSN has been a part of the internet of thing (IoT) component that focuses on future wireless technologies systems. Generally, WSN and IoT device is a controlled application to collect data from various sensors. Then this data information will be sent over the Internet to connect the virtual and real worlds [1]–[4]. This data can be processed according to the needs of the application. Figure 1 shows an example of a WSN operation in a forest to obtain temperature data around the forest. Many innovations and applications related to WSN are involved in various fields such as environmental, automation, agriculture, health, security, military, home, and other commercial applications [5]–[8]. The technology concept can be represented as a connection between humans, computers, and things.

Nevertheless, there are challenges in the use of WSN devices, especially in remote areas. The main challenge is from the energy required to power the device. For now, the use of disposable batteries is one of the solutions. However, the challenge of keeping it functioning for a longer time is extremely difficult. Therefore, many studies and proposals are available to use alternative energy, such as renewable energy or energy harvesting sources. For example the energy can be used such as solar/light [9]–[13], wind [14]–[16],

heat [17]–[19], piezo vibrations [20]–[22], and radio frequency signals (RF) [23]–[25]. One of the solutions that will be discussed in this paper is energy intake using thermal. As it is well known, thermal energy is an abundant supply and can be found anywhere.

According to A. N. Z. Sanusi *et al*., nature is influenced by various factors such as microclimate, topography, surrounding environment, the plants, and arrangement of buildings. Thus, all these factors contribute to different ambient air temperatures [26]. Research by I. S. Muhammad *et al*. was conducted in Gombak, Malaysia. His study's results have shown that the temperature becomes more stable as the more profound the soil is compared to the ambient air temperature [27].

There are several research studies on thermoelectric generator (TEG) modules that have been selected as energy harvesting sources for temperature monitoring applications in forests or conceptual environments of IoT networks. Pullwitt *et al*. conducted a study with soil temperature monitoring for one year in Germany (consisting of four seasons) [28]. There were eight layers of depth readings taken during the day and night. Through the study results, TEG can be used as an energy source to power electronic devices. In contrast to J. Chen and Z. L. Wang [29] has made a thermoelectric study with heat pipe design on the ground surface for WSN application. The output obtained from a temperature difference of 20 ℃ is 298 mV. In comparison, studies using TEG by K. Chottirapong *et al*. to obtain a long lifespan using two concepts of energy storage [30]. There is primary storage of super capacitors, and secondary storage of batteries used for power management is proposed. An output voltage of 15 mW with four TEG connections in series can be used for an unlimited period.

Besides, C. P. de Souza and O. Baiocchi [31] have conducted a study of thermal energy harvesting from the environment on trees, with the average thermoelectric output voltage achieved being about 35 mV. Improvements by using a DC-DC integrated voltage step-up circuit such as the LTC3108 to achieve the minimum voltage target on IoT devices [31]. Based on the manual, this circuit is capable of operating from at least 20 mV to produce 3.3 V, which can turn on the IoT device.

There is research that combines the use of commercial thermal energy generators with solar energy using hybrid photovoltaic systems. The results of the experiments conducted by Z. Zhang *et al.* showed that one TEG module is capable of generating 4.7 mW of power for a WSN node at 3.75x104 lux illumination during full daylight [32]. However, the energy consumption is not effective in the actual situation in the industry. A study conducted by A. Prijic *et al*. used thermal energy harvesting for temperature measurements with small, compact circuits and rigid mechanical structures [33]. However, the system is based on a subscription TEG (custom TEG) and a subscription sensor node. Therefore, it does not show that commercial sensors successfully generate electricity by TEG.

This paper proposes a concept of utilizing a thermoelectric device to convert thermal energy into electrical power, as well as a feasibility study on whether this approach could supply a WSN. The study area coverage is at the garden located in Melaka, Malaysia. The soil's temperature profile of five depth has been studied to find the optimum depth for maximum temperature differences between ambient air and the soil. Using the data collected, the TEG efficiency with different configurations was tested in the lab. This research study will focus on thermoelectric energy harvesting that involves generating small amounts of electrical power to drive circuits in wireless communication electronic devices.

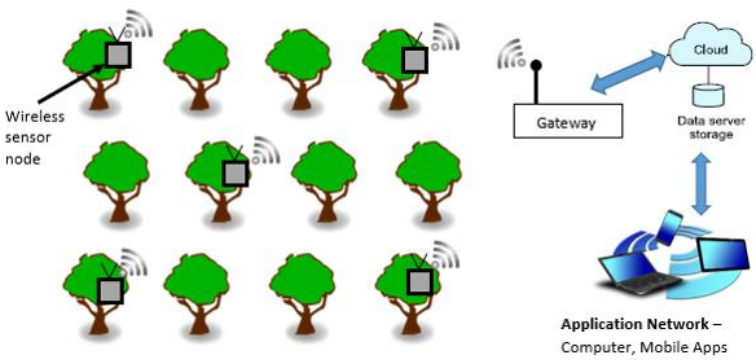

Figure 1. A typical IoT-WSN system in the forest area

2. BASIC PRINCIPLE OF THERMOELECTRIC ENERGY GENERATION

In 1821, Thomas Johann Seeback was the first person to conduct research and invented the Thermoelectric or Seeback effect method. During the experiment, two metal wire connections with one plate

end of the heated side and another side plate with lower temperature (cold) were found to produce electricity. The Seeback effect method and thermodynamic principle, when there is a temperature difference between the two plates, will cause the transition of the electrons present in the thermoelectric construction. The electron transition moves from the n-type to the p-type semiconductor. Therefore, these phenomena will generate direct current flows through the circuit. Figure 2 shows the heat transfer phenomenon to this electricity when a thermal gradient between two plates or feet of the thermoelectric device occurs.

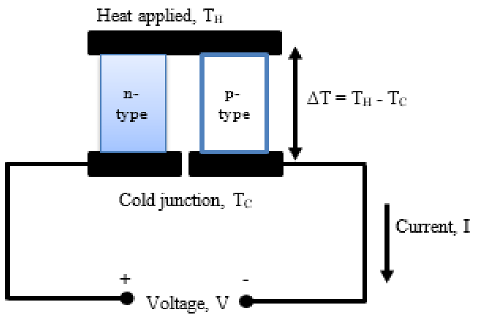

Figure 2. Concept of thermoelectric generators

The basic structure of thermoelectric construction is composed of p-type and n-type materials. Both of these materials will be connected electrically and in parallel with heat. As it is known, thermoelectric can work in two conditions, namely heating and cooling. Electricity generation occurs when there is a temperature difference on the two thermoelectric plates. In contrast, the temperature is generated when the voltage input is supplied.

The thermal modelling of a thermoelectric is derived by considering the thermal effects involved in the heat transfer process. Some of the effects that need to be considered in deriving thermal models of thermoelectricity are the thermal conduction effects, Joule, Peltier, Seeback and Thomson. However, the Thomson effect illustrated by the derivation of the Seeback effect in time function is neglected due to its small value [34].

Most thermoelectric modules have high thermal conduction values between the two plates. This is to ensure that the heat distribution is evenly distributed. The heat conductivity is following the Fourier law of heat transfer, Qtc is presented as (1).

$$Q_{tc} = -\Delta T\, K_{tc} \tag{1}$$

Where Ktc is the thermal conductivity and ΔT is the temperature difference between the two plates (hot and cold plates). Then, the heat Joule effect (Q_{joule}) is generated when an electric current (I) flows on both thermoelectric plates. These mathematical equations can be expressed as (2).

$$Q_{joule} = I^2 R \tag{2}$$

Where R represents the electric resistance. Subsequent heating results when the flow of electricity at two different intersections is called a Peltier effect. The Peltier effect can be represented as (3).

$$Q_{Peltier} = \alpha\, \Delta T\, I \tag{3}$$

Where α is the Seeback coefficient for the thermoelectric. The Seeback effect is due to the difference in temperature between the two thermoelectric plates resulting in an output voltage at these two junctions. The equation of this Seeback effect or coefficient is given as (4).

$$\alpha = V / \Delta T \tag{4}$$

where V is the voltage, T_H is hot temperature and T_C is cold temperature. A thermoelectric structure can be simplified, as shown in Figure 3. In (4) can be referred to in Figure 3 with the output voltage generated based on the difference between the two thermoelectric plates' heat and cold temperatures.

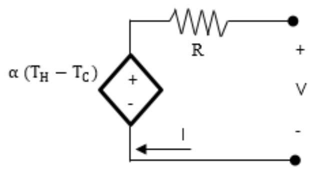

Figure 3. Model of thevenin equivalent circuit in thermoelectric

3. RESEARCH METHOD

The methodology divided into two parts which consists of data temperature gradient measurement and TEG configuration as well as lab measurement based on temperature profile data.

3.1. Data temperature monitoring

Model development and temperature profile monitoring analysis was carried out. The process of monitoring the temperature profile (heat) between the soil surface with several layers of soil depth was carried out around the garden area in Melaka for 46 days. Figure 4 shows a temperature profile monitoring experiment for five depth levels in the soil. Figure 5 shows six JK type thermocouple sensors was used as temperature measurement. This sensor was connected to a WSN device developed using Arduino UNO and LORA shield IoT.

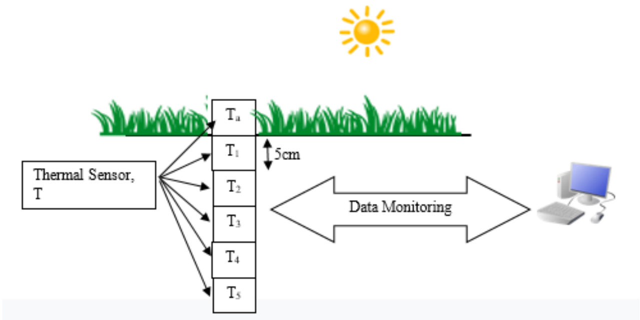

Figure 4. Soil temperature profile monitoring system

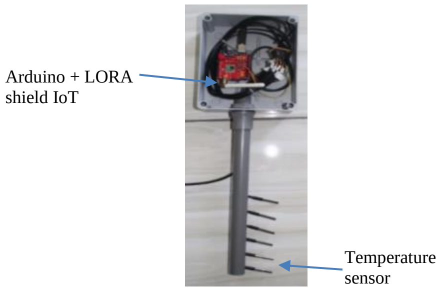

Figure 5. WSN for temperature monitoring system hardware

Information data was transmitted wirelessly using the long range wide area network (LoRaWAN) system architecture. The transmission of this data will go through several protocols the IoT system. The first step of data transmission is through the LoRaWAN protocol. At the same time, IoT LoRaWAN Gateway is a connecting device between sensors, controllers and the cloud. The final process is the analysis of information that can be seen through the graph of the temperature difference of the depth layer with the soil surface. The complete system flow is shown in Figure 6.

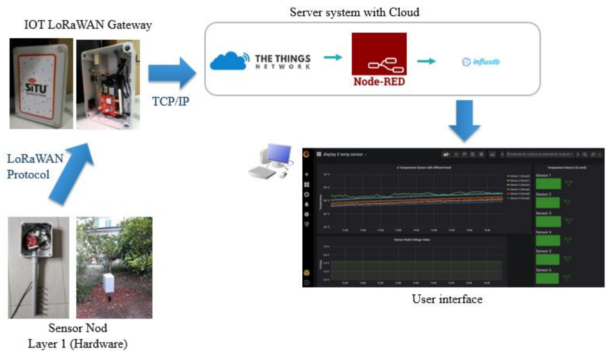

Figure 6. The entire temperature monitoring system, from soil depth differences to IoT network application

3.2. TEG configuration and lab measurement

This section verifies the characteristics and configuration of the arrangement of TEG modules that provides maximum power based on the temperature profile from previous data. In this setup, the TEG SP1848 was used to combine electrical connections in series and parallel. Figure 7 shows the TEG SP1848 information that has been implemented.

The experiments were carried out in the laboratory using thermal equipment to be connected to a thermoelectric module. Five variations of tests have been conducted using three TEG with the model TEG SP1848 measuring at 40x40 mm, to evaluate its performances. The tests were carried out as follow: 1) single TEG,(2) two TEG in series, 3) three TEG in series, 4) two TEG in parallel and 5) three TEG in parallel. Figure 8 shows the connection of laboratory test setup. Analysis of simulation and experimental data based on the temperature difference graph profile against the output voltage was obtained.

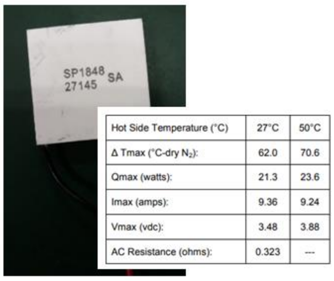

Figure 7. TEG SP1848

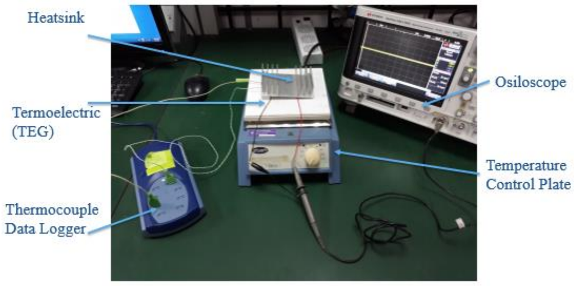

Figure 8. Test setup for TEG testing

4. RESULTS AND ANALYSIS

In this section, the overall thermal energy harvesting system has been tested to power up the electronic load which is the Arduino Uno.

3.1. Data temperature monitoring

The temperature difference between surface and soil by the garden in Melaka has been studied for 1.5 months between 15 July 2020 until 30 August 2020 (46 days). There are five depths were fixed at 3 cm, 6 cm, 9 cm, 12 cm and 15 cm. From the graph plotted in Figure 9, it can be seen that the overall data were taken for 46 days. The pattern is almost the same every day, with an average temperature between 25 °C and 29 °C. Then from the seven day data in Figure 10, it can be seen when the deeper the depth of soil, the temperature becomes more stable (sensor 3, sensor 4, sensor 5 and sensor 6). Therefore, it gives a more significant difference of temperature with surface temperature by reference. In fact, the depth between sensor 1 and sensor 3 (6 cm) shows a similar temperature profile pattern as the surface of the soil.

From the graph plotted for one day, as shown in Figure 11, it can be clearly seen that the deeper the depth of soil, the temperature becomes more stable. Therefore, it gives a bigger difference of temperature with surface temperature by reference. In fact, the depth of 10 cm shows a similar temperature profile pattern as the surface of the soil. ΔT = 1 °C.

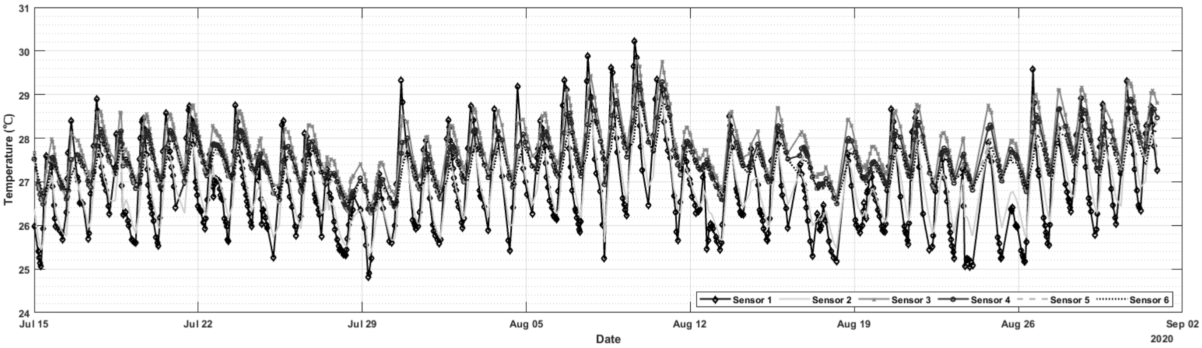

Figure 9. 46-day measurement (15 July 2020 to 30 August 2020)

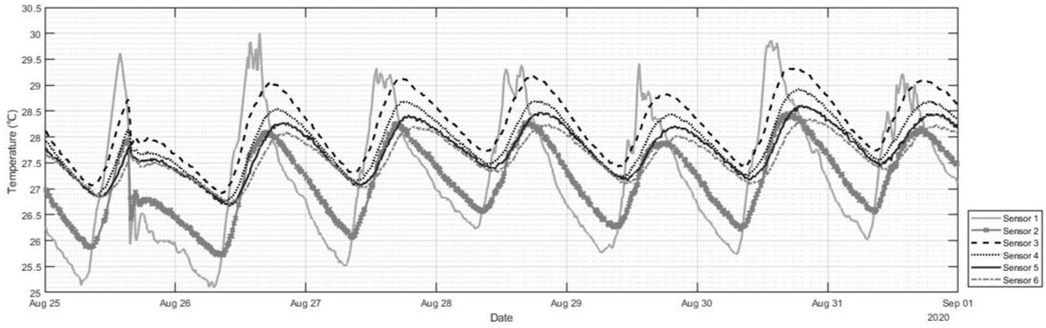

Figure 10. 7-day measurement (25 August 2020 to 31 August 2020)

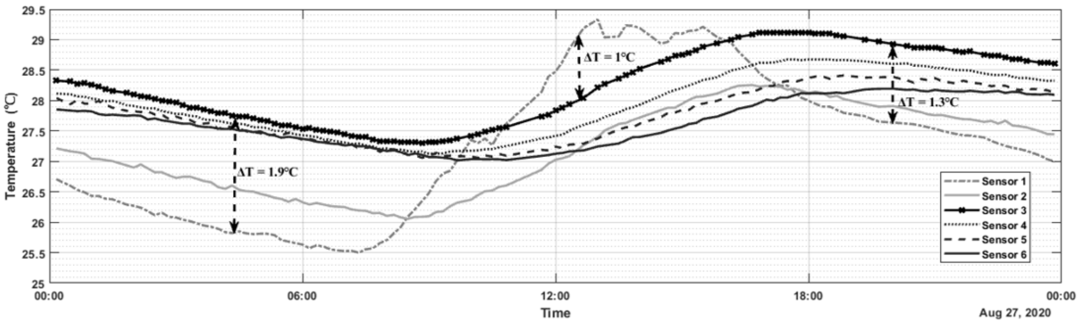

Figure 11. One-day chart measurement (27 August 2020)

Based on Table 1, the depth position between sensor 1 and sensor 3 will give the optimal average temperature difference compared to the other combinations. Where the distance of sensors 1 and 3 is as much as 6 cm. The estimated average temperature difference is more than 1 ℃. Therefore, based on these data results, it can be estimated that this combination of 6 cm distance can give the optimum temperature to the TEG operation. The advantage of this data showing that it can harvest energy regardless of day or night as there will be a temperature difference when the temperature profile switched.

Table 1. Average temperatures for each sensor depth difference

Date	$\Delta(T_{S1}-T_{S2})$	$\Delta(T_{S1}-T_{S3})$	$\Delta(T_{S1}-T_{S4})$	$\Delta(T_{S1}-T_{S5})$	$\Delta(T_{S1}-T_{S6})$	$\Delta(T_{S2}-T_{S3})$	$\Delta(T_{S2}-T_{S4})$	$\Delta(T_{S2}-T_{S5})$	$\Delta(T_{S2}-T_{S6})$	$\Delta(T_{S3}-T_{S4})$	$\Delta(T_{S3}-T_{S5})$	$\Delta(T_{S3}-T_{S6})$	$\Delta(T_{S4}-T_{S5})$	$\Delta(T_{S4}-T_{S6})$	$\Delta(T_{S5}-T_{S6})$
Average	0.51	1.07	0.96	0.96	1.00	1.02	0.72	0.62	0.66	0.30	0.44	0.45	0.15	0.18	0.10

3.2. TEG 1848 lab measurement

The data collected based on five variations of the test on the performance of TEG has been analysed and plotted onto a graph. There are five combinations consists of series and parallel of heat arrangement with series electrically arrangement test as shown in Figure 12. A graph in Figure 13 showing the voltage generated by series and parallel connection of the TEG SP1848 model. It can be clearly seen that as the number of TEG in series connections increases, the voltage generated increases linearly too. It shows the scaling properties of TEG. Based on result from section 3.1, the experimental results in this section have been simplified to Table 2. Variation of data will be shown from temperature start at 1-2 ℃. From the result, the combination of three TEG in series shows in 1 ℃ it will produce output voltage around 0.1 V. It is improving 60% compared to combinations of 2 TEG in series connection from 40 mV. Single TEG will produce the lowest output of voltage. While, series connection will produce more output compare to parallel connection.

The DC1664 board featuring the LTC3109 IC from Linear Technologies is a simple DC-DC step up converter model that supports a minimum voltage of 50 mV. From this board, it selectable performance up to 5V. The standard use of this board can be seen in [35-36], which looked into the production of power from ultra low voltage. Figure 14 depicts an example of a block diagram of TEG based power supply. Petr P. Hawliczek *et al.* [37], reviewed several ultra low voltage step up converters that can be used to supply power into various low consumption devices.

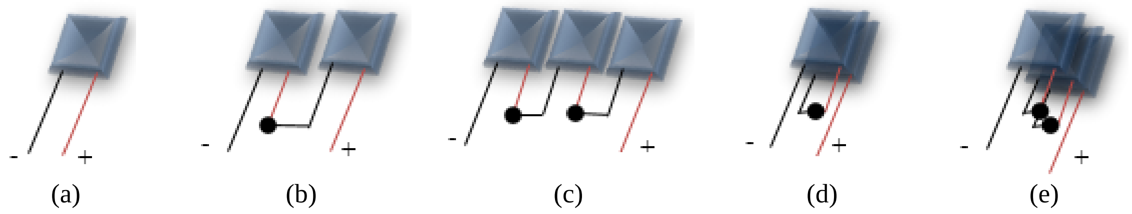

Figure 12. Variation of TEG combination with connection: (a) single TEG, (b) 2 TEG series, (c) 3 TEG series, (d) 2 TEG parallel, and (e) 3 TEG parallel

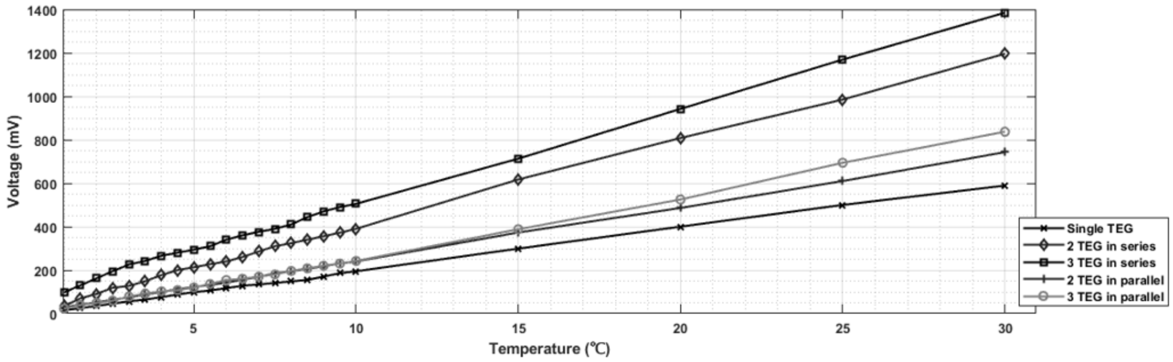

Figure 13. TEG SP1848 performance test

Table 2. TEG SP1848 result based on temperature different between 1 °C to 2 °C

No	Temperature different (°C)	Voltage generates (mV)				
		Single TEG	2 TEG series	3 TEG series	2 TEG parallel	3 TEG parallel
1	1.0	15	35	98	28	22
2	1.2	20	50	110	32	30
3	1.4	22	64	123	38	37
4	1.6	28	75	138	41	40
5	1.8	30	81	150	48	47
6	2.0	35	90	162	52	49

Figure 14. TEG based power supply block diagram

5. CONCLUSION

A thermal energy harvesting system based on the temperature of ambient air and soil is developed and tested. The study area coverage is at the garden located in Melaka, Malaysia. There are five different depths study with a depth between sensor 1 and 3 (6 cm) giving a maximum reading in average temperature reading of 1 °C. Then, TEG characteristics have been tested based on temperature gradient data differences between surface and soil depth. There is a combination of number TEG connection with series and parallel was tested. A single TEG will produce the lowest voltage output compare to using more than one TEG module in series. While, from the experiments conducted the series connection will produce more output compared to parallel connection. At an average temperature of 1 °C, a combination of three TEG SP1848 models will produce an adequate voltage of 0.1 V. The circuit DC1664 was used to increase the TEG output frequency due to its low reliability, and its performance was evaluated in the lab. It needs at least 50 mV to run and can raise or move up the input voltage up to selectable output up to 3 V. The advantage of this system is that it can harvest energy regardless of day or night as there will be a temperature difference when the temperature profile switched. The following is a few suggestions to improve this system further. Firstly, load matching influences a lot on the output of TEG. Maximum efficiency of TEG can be attained when the total resistance of the load is equal to the internal resistance of TEG. Second, since the energy harvesting of

thermal using TEG is very low, probably it can be integrated with a different type of energy harvesting devices, especially solar energy harvesting device. Many studies have been made in solar-thermal hybrid energy harvesting. Also, the system can be augmented with the use of energy storage systems.

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